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EDITED BY MAJOR W. A. HARRISON,

SECRETARY, R.E. INSTITUTE.

PAPER 4.

VOLUME 3.

TELEPHONE TRANSMISSION.

BY

CAPT. A. D. ST. G. BREMNER, R.E.

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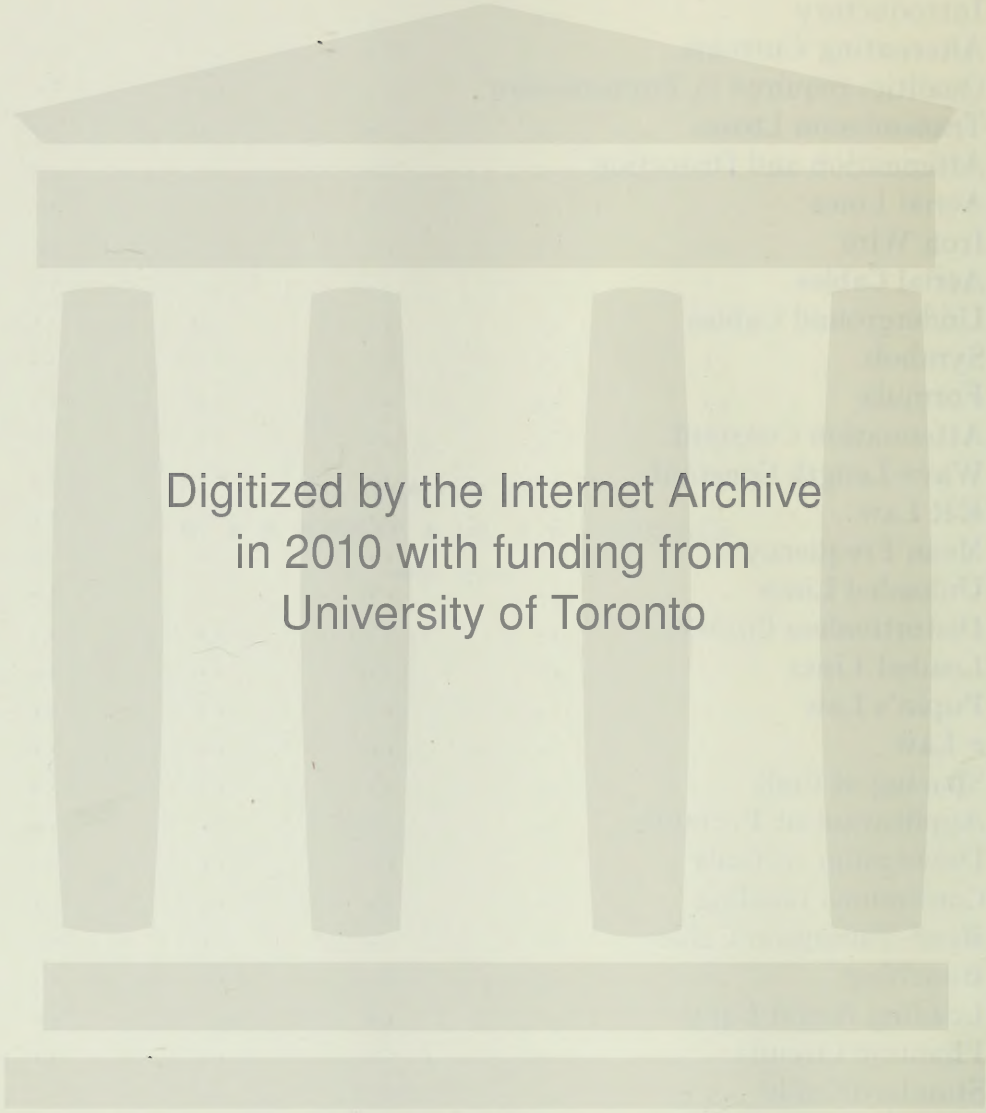
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TELEPHONE TRANSMISSION.

ALL War Department telephone areas in the United Kingdom are now connected to the Post Office and other civilian systems, so that every W.D. telephone may be used for conversation over trunk lines.

It is therefore necessary for R.E. Officers in charge of Telephones to study the subject of telephone transmission and to fully recognize its very decided limitations. No military textbooks on the subject have yet been published and there are few standard works to be obtained, and it is hoped that the following notes, which summarize our present knowledge, will be of assistance in dealing with this problem, which is becoming more soluble every day.

The theoretical portion is very complicated and has been eliminated from these notes as far as possible, as it would require too much space for its elucidation.

If further knowledge is required as to how the various formulæ, etc., have been derived, reference may be made to the Bibliography given at the end.

For practical purposes, only a small acquaintance with electricity, including alternating currents, is really necessary.

The problem of telephonic transmission is essentially different from that of telegraphic transmission.

When a telephone transmitter is spoken into, the sound waves impinging on the diaphragm cause it to vibrate, and, by the consequent variation of the electrical resistance of the transmitting circuit, a series of alternating currents are sent out to line ; the circuit is now always metallic throughout.

These currents are subject to certain losses in transmission and on arrival at the other end cause the diaphragm of the receiver to vibrate, due to the variation in the magnetic field ; these vibrations emit sound waves which are received by the auditory nerves in the ear and the conversation is thus conveyed to the brain.

No less than ten transformations take place, and it is marvellous to think that a telephone receiver will convey an intelligible and commercial conversation when actuated by one-tenth of a milliampère, or less than 1 per cent. of the current put into the line.

ALTERNATING CURRENTS.

Alternating currents possess the following characteristics :—

(*a*). Frequency.
(*b*). Amplitude.
(*c*). Wave length.
(*d*). Velocity.
(*e*). Wave form.

And they may be represented by a simple sine curve.

(*a*). The frequency is the number of complete reversals per second. A complete reversal is known as a cycle or period.

(*b*). The amplitude or extent of vibration from the zero line represents the maximum strength of the current.

(*c*). The wave length represents the distance in miles traversed by a wave in making a complete cycle.

(*d*). The velocity is the speed at which the wave travels, and the velocity of a simple periodic wave depends on the wave length. It can never exceed the velocity of light which is 192,000 miles per second nearly.

(*e*). The wave form is the shape of the curve in passing through a complete cycle. Two alternating currents with the same frequency and amplitude may differ materially in wave form.

In telephonic transmission :—

The wave length or frequency determines the number of vibrations per second of the receiver diaphragm and consequently the pitch of the sound.

The amplitude governs the extent of these vibrations and hence the volume of the sound.

The wave form governs the timbre or quality of the sound and so affects the articulation.

It is essential that the wave form of the received current should be as nearly like that of the sent-out current as possible.

It must be clearly understood that human speech produces currents of complex wave form, made up of the sum of simple sine curves, differing in phase and amplitude with wave lengths or frequencies (between 100 and 2,000 per second) in harmonic relation, and that therefore the ordinary formulæ for alternating currents do not apply.

The average speech wave of a male voice consists of a fundamental lying between 100 and 300, and an important harmonic somewhere between 700 and 1,000 per second which considerably exceeds the fundamental in amplitude. In the female voice the fundamental is

much higher, but the important harmonic is somewhat lower than the corresponding harmonic in the male voice.

This accounts for the fact that the female voice transmits better over a long-distance line, since there is less distortion.

These complex wave curves can be resolved into their component simple sine curves by means of Fourier's Theorem, which cannot be discussed in these notes for want of space.

In order that speech may be perfectly transmitted, all these waves must travel with equal velocity to the receiving end and must moreover be equally attenuated. Attenuation is the dying away of the amplitude of the current wave as it travels along the circuit.

If equal speeds are not maintained, the various components of the speech wave will be distorted in phase, and the harmonics that lag in phase will also interfere with other sounds immediately following. If also a fundamental note and its harmonics are not equally attenuated, their proper relative loudness will not be maintained and distortion will occur.

The two qualities essential in telephonically transmitted speech are (*a*), sufficient loudness or volume of sound; (*b*), clearness or distinctness.

The loss of volume is due to the attenuation generally but the loss of clearness is due to the difference in the attenuation of the different harmonic frequencies and consequent distortion of the wave form.

It may be interesting to note that "oo" is the most efficient vowel sound, while "S" and "R" are the most inefficient, being of very high frequency (1,500—2,000 per second). Any sibilant sound is difficult to transmit.

TRANSMISSION LOSSES.

In a telephone circuit there are four main constants which affect the transmission :—

(*a*). Resistance.
(*b*). Inductance.
(*c*). Electrostatic capacity.
(*d*). Leakance (reciprocal of insulation resistance).

The capacity generally stated is the wire-to-wire or mutual value, which is about 70 per cent. of the wire-to-earth value; this latter term is falling into disuse with the abolition of earth-return circuits.

There is no definite relation between these constants, in the sense that if three are known, the fourth may be determined; consequently the investigation of their joint influence on the transmission of speech is somewhat complex.

There are also other causes of loss, which must be taken into account and are not so obvious :—

(*e*). Abrupt and numerous alterations in the circuit which may cause reflection of the waves.

(*f*). Interference from extraneous cause, *i.e.*, static or magnetic induction, leakage, etc., from neighbouring circuits.

(*g*). When a varying current, especially one of high frequency such as a telephonic current, flows in a circuit, eddy currents are produced in any conducting material near the main conductor and such currents react so as to oppose the rise and fall in strength of the main current. Eddy currents, for instance, flow in the receiver diaphragm and affect its proper working.

(*h*). If there is any iron near the main conductor, the iron will be reversely magnetized with each alternation, and consequently there will be a definite hysteresis loss in the iron.

The effective resistance of the main circuit will therefore be made up of the ohmic resistance (that offered to steady currents) and that due to the effect of eddy currents and hysteresis.

In any ordinary telephone circuit of revolved wires (overhead, buried, or submarine) without special treatment, the difference between effective and ohmic resistance is practically negligible.

This is by no means the case where inductance or loading coils which contain masses of copper or iron are introduced into the circuit, or where heavy gauge wires are used.

Methods of increasing the inductance of a circuit are not difficult to find ; the real problem is to devise a method which does not largely increase the effective resistance at the same time. The advantages of increasing the inductance are explained later.

In circuits free from iron, the inductance may be considered as constant for all currents and frequencies, but with circuits loaded with iron-core coils this is not quite true. However by properly selecting the quality and properly arranging the quantity of iron, uniformity of inductance for all important telephonic frequencies (500—2,000 per second) may be closely obtained.

It should be noted that resistance and leakage losses are absolute, and are not comparable with inductance and capacity effects which delay the passage of the current impulses and in which the energy is stored, not lost.

In any telephonic apparatus the high-frequency current in the conductor is not uniformly distributed over the cross section of the wire, and the current in neighbouring turns of wire furthermore increases this non-uniformity ; these effects also increase the effective resistance of the apparatus, together with eddy currents and hysteresis.

Theoretical investigations have been made by many scientists, including Maxwell, Kelvin, Heaviside, Campbell, Pupin, Kennelly, Hayes and others.

ATTENUATION AND DISTORTION.

The alternating current waves in a long circuit suffer from:—

(*a*). Attenuation.
(*b*). Distortion.

Attenuation is the rate at which the amplitude is decreased and it reduces the volume of sound. It varies almost directly with resistance and capacity and inversely with inductance up to a certain point.

Distortion is the alteration in wave form, which changes the quality of the sound wave and consequently the articulation.

Attenuation is produced by the resistance of the circuit and also by leakage due to imperfect insulation shunting away a portion of the current from the receiver. The result, though reducing the volume of sound, is not altogether detrimental if the articulation remains good (as it does in an aerial circuit of small capacity), because the human ear can pick up the minutest sounds.

In an underground circuit with comparatively large capacity, a further attenuation is produced by what is known as the " tailing effect," *i.e.*, the effect of capacity is to cause the wave to spread out, both forwards and backwards, causing distortion not only of the wave itself but also of the neighbouring impulses, with which it interferes. This is the cause of the " back talk " in the receiver.

The distortion of impulses is due to the rush of charge into the dielectric and the incomplete discharge between successive impulses.

This distortion affects waves of higher frequencies much more than those of lower frequencies ; it eliminates the higher notes and harmonics, flattens the upper or overtones and in extreme cases makes the sound inarticulate, though the volume may be ample.

In all ordinary cables, Resistance × Capacity is greater than the Inductance × Leakance, therefore the lower the frequency, the less the attenuation and wave velocity, but the greater the wave length.

Hence shorter waves travel faster and attenuate more rapidly. There is also a certain amount of distortion introduced by the diaphragm of the transmitter, due to mechanical resonance which sometimes occurs, and also by electro-mechanical resonance in the diaphragm of the receiver. Inductance in a circuit acts as a kind of inertia ; it opposes all rapid changes in the impulses and thus slows down the rapid capacity charge and also the " tailing " discharge, in this way minimizing the attenuation and distortion.

The attenuation varies much less with change of frequency when

inductance is added. Inductance predominates over the capacity on short lengths, but, as the length increases, the capacity effects increase more rapidly than the inductance and a point is reached where they neutralize each other.

In virtue of the slowing down of the rate of wave propagation or velocity, a circuit of large inductance can store up a given quantity of magnetic energy with a smaller current than a circuit of small inductance, and therefore, as with small currents the heat losses ($C^2 R$) will be less than with large currents and as smaller heat losses mean less attenuation, there must necessarily be an increase in efficiency of transmission.

At present, volume and not articulation is considered the most important, owing to the instinctive quality of the human ear in recognizing what must be the merest phantoms of speech vibrations.

If apparatus is improved, the line distortion can be no longer neglected, but it is not serious in aerial circuits up to 1,000 miles and in cables up to 20 miles in length.

The formulæ given ignore articulation altogether ; it is now however allowed for, in loaded circuits at any rate, by inserting a minimum number of loading coils per wave length.

The actual practical limit is fixed by the loss in amplitude of the wave, *i.e.*, by diminution in volume rather than by the loss of articulation ; although when the limit is approached, articulation begins to suffer and the tones become low and hoarse, making speech impracticable.

Calculations based on attenuation only, which take resistance, capacity, inductance and leakance into account, are found to agree with actual experimental facts, except perhaps on aerial lines where the insulation is variable.

It is interesting to note that nearly half the total mileage recorded as the limit of commercial speech in any made-up trunk line is absorbed in exchanges and subscribers' lines.

AERIAL LINES.

The construction and maintenance of aerial lines are so well known, and there are so many textbooks on the subject, that there is no necessity to enter into details here. It is sufficient to point out that aerial lines are usually constructed of heavier gauge wires, bronze in the shorter lines and copper in the longer ones, and that they possess higher inherent inductance but lower capacity than underground cables. Aerial lines are thus more efficient than underground cables, even though the insulation resistance is much lower, but they suffer from greater liability to damage by storms and evilly-disposed persons.

They are also much more subject to disturbances from external

sources, so that it is very important that the wires should be revolved or crossed, carefully regulated and symmetrically constructed, each pair being of the same gauge and material, and that the insulation should be equal on both limbs in order to balance the circuit properly. Dry, *i.e.* unsoldered, joints should be avoided.

The question of revolving *versus* crossing wires is certainly debatable. On the Continent and in America wires are usually crossed, but in England they are generally revolved; the latter is more suited to W.D. requirements. *Instruction in Army Telephony* maintains that all wires should be revolved, to eliminate external disturbances, and if two or more groups of four wires are erected on the same line of poles they should be crossed in addition, to eliminate overhearing between groups. This is really a counsel of perfection and applicable only to long lines.

Earlier efforts at telephone transmission tried to reproduce every harmonic and every overtone. Consequently 800-lb. copper aerial was used for the London–Glasgow trunk line, worth £30,000 for copper alone.

As a matter of fact this line has only an actual transmission efficiency of $\frac{3}{4}$ of what it ought to have theoretically, because of interspersed lengths of cable, numerous protective devices and restrictions by local authorities.

The speaking from London to Aberdeen was found to be good, but extension to Inverness proved to be the limit. Similarly London to Marseilles *viâ* Paris was good, but Nice was beyond the limit.

With the 1910 loaded cable across the Dover Straits, it is now possible to speak from Aberdeen to Paris—a distance of 900 miles.

IRON WIRE.

Unlike copper wire, the resistance of iron wire varies directly, and the inductance inversely, as the frequency.

Thus a 400-lb. iron wire has a resistance of 26 ohms and an inductance of 15 millihenries with a steady current, but these values change to 55 ohms and 4 millihenries with an alternating current of frequency 750.

This is due to the "skin effect," as the current does not penetrate into the centre of the wire. The variations, however, in the resistance of telephone conductors of average diameter are negligible with telephonic frequencies. After some time also iron wire becomes oxidized, especially near the sea. Owing to its high resistance and low inductance, it is unsuitable for long-distance circuits.

Under certain conditions and in favourable localities, it may pay very well to use iron wire. The question is one rather of engineering costs and the standard of transmission desired than of any moral objection to the use of iron.

AERIAL CABLES.

Aerial cables are often used to supplement or replace open wires. Their manufacture and transmission efficiency are generally similar to underground cables.

UNDERGROUND CABLES.

Lead-covered, air-space, paper-insulated cables have been exclusively used by the General Post Office since 1905 for underground circuits.

Their advantages are :—

(1). Economy of space.
(2). Lower capital cost per wire.
(3). Lower cost of maintenance.
(4). Greater durability.
(5). Lower electrostatic capacity.

Their disadvantage is that a defect in the lead sheathing, which permits the ingress of damp air, will probably result in the complete breakdown of all the circuits in the cable affected.

This can be obviated to a large extent by using a number of small cables, say not exceeding 14 wires each, instead of a single multiple cable on any particular route, or by putting in solid plugs at intervals to limit the damage to the section affected.

The electrostatic capacity depends largely on the looseness or otherwise of the paper wrapping, which provides an air space, more or less, round the conductors. Short-distance cables to an exchange can be more tightly twisted than those on trunk lines.

The wires in a cable may be laid up in either, or a combination of the following formations :—(*a*) Twin, (*b*) multiple twin, (*c*) quadruple pair, or (*d*) single wire, each wire being covered with a screen of metal tape.

(*a*). *Twin.*—Two conductors are twisted together to form a pair, with lay of 3 in. Any other pairs to make up a cable are twisted round this centre pair with lays of 4 in., 5 in., 6 in. in sequence.

(*b*). *Multiple Twin.*—4-wire cores. Two 2-wire cores made as in (*a*) are twisted together to form a 4-wire core. Other 4-wire cores are added with different lays to make up a particular cable. For wires of 100 lbs, per mile and over. Similarly for 8-wire cores.

The object of this method of construction is to provide a cable which will permit of circuits being super

imposed upon pairs in the same core, which are individually used for other circuits.

When required, single wires or cores made up as above may be placed between the larger-sized cores and are termed "worming" cores.

(*c*). *Quadruple Pair.*—This consists of one or more cores, each containing four twisted pairs laid up together round a centre yarn, forming a "quadruple pair" core.

This type was introduced for the same purpose as (*b*), by which it is being superseded.

When superimposing, diagonal pairs in the same core are used. Worming cores may be added as in (*b*).

(*d*). *Single* (*Screened*).—Each conductor is covered with three wrappings of paper, over which is wound helically soft copper tape about 3 mils. thick and $\frac{1}{4}$ to $\frac{3}{8}$ in. wide having an overlap measuring 30 per cent. of the width of the tape used.

The object is to permit single wires to be used for telegraph circuits without interference with the working of other circuits in the same cable. The screening tape is in contact with the lead sheath and therefore earthed.

(*a*) (*b*) or (*c*) and (*d*) can be combined into one cable as required. Joints are made every 176 yards or thereabouts.

Jointing Multiple Twin Cables.—As each of the differently coloured pairs of wires is laid up with a distinctive lay, it is necessary to follow a definite plan in jointing the pairs together, in order to secure the greatest immunity from inductive disturbance

At each joint the pairs are connected as follows:—

White pair to green pair.
Red ,, blue ,,
Green ,, red ,,
Blue ,, white ,,

Each pair is thus of equal resistance in any particular length of circuit. Individual wires or pairs must not cross from one core to another. The most convenient main cores are jointed together irrespective of colours.

Jointing Quad.-Pair Cables.—The colours of the pairs are red, blue, green and white, in order of length of lay. The red and green pairs are diagonally opposite the white and blue pairs respectively.

In any quad.-pair core, similarly coloured pairs are not jointed together.

The diagonal positions of the pairs must be maintained.

Each quad.-pair core has a paper wrapping of a distinctive colour and cores of dissimilar colours are always connected together.

Circuits composed of cable alone, can be worked with a less volume of sound than open circuits, because the latter, liable as they are to great changes in insulation, never afford the efficiency theoretically allowed and are also much more subject to external disturbances. This means that heavier conductors must be employed than would otherwise be necessary, while in a cable this extra reserve of power is not required because the efficiency once established is always the same.

A minimum insulation resistance with direct current of 5,000 megohms per mile, between any one conductor and all the other conductors and lead sheathing connected to earth, can be obtained. Béla Gáti showed that ordinary paper cables have a much lower insulation resistance with alternating currents at frequencies comprised within the limits of human speech.

A fall in the insulation resistance causes an increase in the capacity, and any increase in temperature causes a fall in insulation resistance and a rise in the capacity. The testing temperature is usually 60° Fahr. As a general rule, conductors up to 40 lbs. per mile are insulated with a single layer of paper applied spirally, and above that size by a single paper applied longitudinally, secured by a whipping of thread.

Any more layers, *ceteris paribus*, only increase the cost and capacity, while the mechanical superiority of double over single insulation is inappreciable.

The mutual, or wire-to-wire capacity, is generally quoted, and is about 70 per cent. of that of a single wire tested against all the other wires and the sheathing earthed, one pole of the battery being also earthed.

The sheathing can be either pure lead or an alloy with up to 3 per cent. of tin to make it harder.

All air-space telephone cables must be laid or drawn into ducts with great care, the cable being uncoiled direct from the drum. If the cable is twisted to any extent, there is great risk of the conductors being brought into contact with each other and the lay of the conductors will certainly become irregular. "Flaking" is therefore not permissible.

The maximum diameter of a telephone cable should be approximately $\frac{1}{6}$th less than the pipe or duct into which it is to be drawn, and never less than $\frac{1}{8}$th.

The best and cheapest duct for W.D. requirements is probably the fibre tube, made by the Key Engineering Company.

The ends of air-space cables are made off into "pot heads" or "cable distribution boxes."

A "pot head" consists of a solid lead plug in which are embedded the rubber or cotton-covered leads, which are used for joining to test frames or apparatus; it hermetically seals the end of the cable.

The insulation of the larger air-space cables is kept up by pumping in dry air occasionally.

As regards comparative costs, small air-space cables cost £4 per mile of wire, G.P. cables £25, rubber cables £8 to £20. The annual cost of maintenance of air-space cables is about 15s. per mile of wire less than G.P.

Air-space cables are made from one pair upwards to 800 pairs; the latter, when of 10-lb. conductors, can be drawn into a 3-in. pipe.

Paper-insulated cables, impregnated with resin, have not been much used for telephone purposes at present, owing to the capacity being higher than the air-space type, but they will probably be adopted by the W.D., as they are about 30 per cent. cheaper than the V.I.R. cables now in use. The 40-lb. G.P. quad. cable, so largely used at present in W.D. buried circuits, is quite unsuitable (see "S.M. cables").

SYMBOLS.

The following symbols will be used throughout :—

Loop = the two wires forming the circuit.

R = total effective resistance in ohms per mile of loop.

r = conductor resistance in ohms per mile of loop.

ρ = effective resistance of loading coils in ohms.

K = wire-to-wire or mutual electrostatic capacity in farads per mile of loop. The steady-current value is generally taken, as it is easier to measure with accuracy, though it is higher than the alternating-current value, which is naturally the right one to use.

k = wire-to-wire capacity in microfarads per mile of loop.

L = total inductance in henries per mile of loop.

= ·001 for underground cables.

·0017 for submarine cables.

·0032 to ·0042 for copper aerial wires.

l = total inductance in millihenries per mile of loop.

i = inductance of loading coil in millihenries.

S = leakance in mhos per mile wire to wire.

This is the reciprocal of insulation resistance in ohms per mile wire to wire.

w = leakance in ohms per mile wire to earth.

$\pi = 3{\cdot}1416$.

n = frequency or periods per second.

P = the angular velocity $= 2\pi n = 5000$ by international agreement.

$e = 2{\cdot}7183$ (base of Napierian logarithms).

W = wave velocity in miles per second $= n\lambda$.

α = wave length or velocity constant.

λ = wave length $= \frac{\text{velocity}}{\text{frequency}} = \frac{2\pi}{\alpha}$ in miles.

β = attenuation constant.

$e^{-\beta}$ = attenuation per mile or ratio in which the maximum values of the current and potential are weakened by travelling a mile along the circuit.

$e^{-\beta x}$ = attenuation factor, where x = length of loop.
$= \cos h\beta x - \sin h\beta x$ in hyperbolic trigonometry.

$j\alpha + \beta$ = propagation constant.

$\frac{L}{R}$ = time constant, affecting heavy aerial and loaded lines.

B × length of loop = efficiency factor or attenuation exponent or length.

$\frac{S}{PK}$ = constant, $\frac{S}{K} = 50$ for air-core coils.
80 for iron-core coils.

Where the loading coils per wave length do not greatly exceed 9 in number at frequency 796 (P = 5000) or π in number at frequency 2000.

D = distance in miles between loading coils.

mil. $= \frac{1}{1000}$ in.

M.S.C. = miles of standard cable.

S.C.E. = standard cable equivalent.

mfd. = microfarad $= \frac{1}{1,000,000}$ farad $= 10^{-6}$ farad.

S.M. = submarine.

G.P. = gutta-percha.

C_S = current sent.
C_R = current received.
$\Big\}\ C_R = C_S \times e^{-\beta x}$

20-lb. cable = a cable with conductor which weighs 20 lbs. per mile.

On the Continent lines are referred to in terms of the conductor diameter.

S.W.G. = standard wire gauge (British).

B. & S. = Brown & Sharpe (American standard wire gauge).

N.T.C. = National Telephone Company.

D.C. = direct current.

A.C. = alternating current.

P.O. = the General Post Office.

C.B. = common battery.

Knot or naut. = a nautical mile = 1·153 miles.

FORMULÆ.

$$\alpha = \sqrt{\tfrac{1}{2}\left[\sqrt{(R^2+P^2L^2)(S^2+P^2K^2)}-(RS-P^2LK)\right]} \quad \ldots\ldots(1).$$

$$\alpha = \sqrt{\tfrac{1}{2}PK\left[\sqrt{(R^2+P^2L^2)}+PL\right]} \quad \ldots\ldots(2).$$

Where S=O or is negligible.

$$\beta = \sqrt{\tfrac{1}{2}\left[\sqrt{(R^2+P^2L^2)(S^2+P^2K^2)}+(RS-P^2LK)\right]} \quad \ldots\ldots(3).$$

$$\beta = \sqrt{\tfrac{1}{2}PK\left[\sqrt{(R^2+P^2L^2)}-PL\right]} \quad \ldots\ldots(4).$$

Where S=O or is negligible.

The above are the ordinary formulæ for unloaded lines.

$$\beta = \frac{\sqrt{k_1}}{20}\sqrt{\sqrt{R_1^2+(5l_1)^2}-5l_1+\frac{200\,R_1}{\omega k_1}+\cdot000128\sqrt{R_1^2+(5l_1)^2}}$$

(single wire values).....(5).

With cables of small conductors, PL is negligible when R is large and S=O :—

$$\alpha \text{ and } \beta = \sqrt{\tfrac{1}{2}PKR} \quad \ldots\ldots(6).$$

When PL is very large and R is small and S=O or is small compared to PK :—

$$\alpha = P\sqrt{LK} \quad \ldots\ldots(7).$$

$$\lambda = \frac{1}{n\sqrt{LK}} \quad \ldots\ldots(8).$$

$$\beta = \frac{R}{2}\sqrt{\frac{K}{L}} \quad \ldots\ldots(9a).$$

If $\frac{PL}{R}=3$ or more, this is accurate enough, where P=5000.

$$\beta = \sqrt{\frac{RS}{2}} \quad \ldots\ldots(9b).$$

$$W = \frac{1}{\sqrt{KL}} \quad \ldots\ldots(10).$$

If S is not zero $\beta = \frac{1}{2}\left(R + L\frac{S}{K}\right)\sqrt{\frac{K}{L}}$ .....(11).

If l_1 is larger than R_1 (in numerical value) and $\omega k_1 = 12{,}500$ approx. for G.P. cables :—

$$\left.\begin{aligned}\beta &= \cdot01183\sqrt{k_1 r_1}\\ l_1 &= 7\cdot14\, r_1\end{aligned}\right\}\text{single wire values}\quad\left\{\begin{aligned}&\ldots\ldots(12).\\ &\ldots\ldots(13).\end{aligned}\right.$$

If KR=LS or if S is not zero :—

$$\alpha = P\sqrt{LK} \quad \ldots\ldots(14).$$

$$\beta = \sqrt{RS} \quad \ldots\ldots(15).$$

$$Dik = 20\cdot4 \text{ to } 25\cdot3 \quad \ldots\ldots(16).$$

ATTENUATION CONSTANT.

This is called the "damping constant" on the Continent.

Some confusion seems to exist as to whether the attenuation constant should be notated α or β. The real constant of telephone transmission is the propagation constant, which is a complex quantity and can be written $j\alpha+\beta$, where the attenuation constant is the real component and the wave-length constant the imaginary component.

The National Physical Laboratory, Dr. Kennelly, Dr. Fleming and other scientists term α the attenuation constant, while the choice of β was originated by Dr. Pupin and is firmly fixed in Germany, France, America and generally in England.

The attenuation constant (β) is based on the C.G.S. units, and represents the fraction of current loss in reduction of amplitude of the wave impulse in the unit length of 1 mile.

For instance, if $\beta=\cdot1$ and original amplitude$=100$, at the end of the 1st mile the amplitude$=100-(100\times\cdot1)=90$, at the end of the 2nd mile$=90-(90\times\cdot1)=81$ and so on. In practice, β may vary from ·0022 for the heaviest type of copper aerial to perhaps ·22 for the lightest gauge ($6\frac{1}{2}$ lbs.) of underground cable at present used, assuming $n=750$.

The attenuation factor ($e^{-\beta x}$) is the factor by which an initial amplitude at the transmitting end has to be multiplied to give the amplitude at the receiving end.

For instance, the amplitude of the above example at 10 miles will be $100\times e^{-\beta\times10}=100\times e^{-1}$

$$=\frac{100}{e}=\frac{100}{2\cdot7183}=36\cdot78.$$

This therefore enables the percentage of current received at any part of the line to be calculated.

The percentage necessary at the end of a circuit to give commercial speech is about 1 per cent. An easy commercial limit is 4 per cent.

The attenuation factor is more often used with current-measuring instruments in the form $C_R=C_S\times e^{-\beta x}$ in order to obtain β.

WAVE-LENGTH CONSTANT.

The wave-length, or velocity constant (a), determines the velocity with which the waves travel along the circuit and is defined to be an angle a in circular measure, such that the phase difference in the currents at two points in a cable separated by a distance $x=ax$.

Hence wave length = velocity ÷ frequency.

$$\text{or}\quad \lambda=\frac{\frac{2\pi n}{a}}{n}=\frac{2\pi}{a}.$$

The KR Law.

In 1854 Lord Kelvin enunciated the "KR" law; this law gives a measure of the efficiency of a telegraph cable, as it affects the speed of signalling, since the frequency is inversely proportional to KR.

Attempts were made to apply this law to telephone work, but it fails where R, K and L vary materially, especially on open lines where self-induction is a marked factor.

Mean Frequency.

From inspection of formulæ (2) and (4), it will be seen that the attenuation and velocity vary directly with the frequency. For purposes of calculation therefore a particular frequency must be assumed in every case.

In 1904 Dr. Hayes (America) demonstrated that an underground cable, when operated in practical telephone conversation at all frequencies between 100 and 2,000, behaves in regard to attenuation virtually as though the frequency was a single one of 800.

Later investigations established the fact that sufficient accuracy is secured by assuming a frequency of 750. It was agreed however at the 2nd International Conference of Engineers of Telephone and Telegraph Administrations, held in Paris in September, 1910, that a frequency of 796 (so that P=5,000) should be taken as a standard for telephonic measurements and that these latter should be made with a pure sine curve wave.

The frequency of 800 has since been proved correct by many experiments, as far as loudness is concerned. When velocity is being considered, as in the case of loaded cables, 2,000 is sometimes taken as the frequency; the reason will be explained later.

Mr. Cohen in 1907 stated that the upper limit for telephonic frequencies of importance is 1,600, but one of the features of harmonics is that successive harmonics become progressively less in intensity, so that 750—800 is much more likely to be the mean of 2,000 rather than of 1,600.

Dr. Kennelly in a recent series of lectures pointed out that 770—800 is the natural period of vibration of the transmitter diaphragm, and put forward the theory that all telephone waves are therefore of general sinusoidal form with one fixed period of about 800, and that different sounds only alter the particular shape of the curve at any point but not the general form of the wave or its period.

If this simpler theory is accepted, all our preconceived ideas on the subject must be reconsidered.

However we may theorize, the present improvements in transmission efficiency have been obtained as a result of practical

experiment and trial and the accuracy of the various formulæ proved beyond a doubt.

At the same time, this new theory may possibly point the way to further improvement.

UNLOADED LINES.

In calculating for overhead lines, the full formula (3) for β should be used, as none of the factors are negligible.

This formula is not very convenient for calculation, because $\sqrt{(R^2+P^2L^2)\,(S^2+P^2K^2)}+RS$ is in the majority of cases so nearly equal to P^2LK that a large error may be made in taking their difference unless each is worked out to many places of decimals.

It may therefore be better expressed as in formula (5), where the values are for single wires, not loop.

In underground or S.M. cable circuits, the insulation resistance wire to wire is high, being between 5 megohms and 5,000 megohms per mile.

Generally therefore if the leakance (S) is not greater than 2×10^{-7} mhos, it may be neglected without producing any appreciable error in the results. Formulæ (1) and (3) will then reduce to (2) and (4) respectively and are applicable to all unloaded cables possessing normal resistance, inductance and capacity. A further simplification is possible in special cases such as when R is high compared to PL; formulæ (2) and (4) will then reduce to (6).

This is only approximately correct, say to within 5 per cent.

DISTORTIONLESS CIRCUITS.

In a circuit with a simple periodic wave of current and containing resistance, capacity and inductance, the effective current

$$=\frac{\text{impressed EMF}}{\sqrt{R^2+\left(PL-\frac{1}{PK}\right)^2}}$$

and the current lags behind the impressed EMF by an angle θ, such that

$$\tan\theta=\frac{PL-\frac{1}{PK}}{R}$$

$\sqrt{R^2+\left(PL-\frac{1}{PK}\right)^2}$ is the impedance of the circuit and $PL-\frac{1}{PK}$ is the reactance, which acts like a resistance and causes a difference of phase in the impressed EMF and the effective current.

If $PL=\frac{1}{PK}$, the inductance and capacity effects balance one another and the impedance equals the simple resistance.

The circuit will then be electrically resonant, syntonic or distortionless; as the impressed EMF is now in phase with the current, Ohm's law can be applied without modification.

Though the calculations are not so simple for telephonic transmission, the above gives an idea of the more elaborate formulæ.

In a distortionless telephone cable, waves of all frequencies would travel at the same rate, viz., $\frac{1}{\sqrt{KL}}$ and attenuate at the same rate, viz., reduce in amplitude by $e^{-\beta}$ per mile.

The distortion in an ordinary telephone cable can be cured theoretically by making the cable have such constants that $KR = LS$.

For example (1) R or K may be reduced.

(2). L or S may be increased, which means in the latter case a decrease in the insulation resistance.

(3). Two or more of these primary constants of the cable may be changed, in order to make KR as nearly equal to LS as possible.

The problem is ultimately one of cost, practicability of construction and maintenance being also taken into account.

If $KR = LS$ in formula (3), it reduces to formula (15). A result apparently independent of the frequency, *i.e.*, all waves would be proportionately attenuated and the circuit distortionless.

But no dielectric, except perhaps air, remains fairly constant in specific inductive capacity and leakance for all telephonic frequencies, while if there is any iron near the conductor, R and L will not remain constant for all frequencies.

Even say by increasing S and taking the lowest present known values for K and R in any case of practical telephony, the resulting attenuation would be so great that, although the articulation might be perfect, the volume or loudness of speech obtained would be too small on a lengthy line to be of any commercial use whatever.

Increase of leakance is scarcely applicable to telephone circuits; for example, a cable with a 20-lb. conductor would be distortionless with an I.R. of 200 ohms per mile but β would be increased six times and a 400-lb. copper aerial would be distortionless with an I.R. of 85,000 ohms per mile, but β would be increased 1·9 times.

There is no doubt that leakage plays a very important part in the transmission of telephonic speech. It increases with higher frequencies.

Dr. Breisig in 1906 made an error of 20 per cent. in calculating β by neglecting the fact that there is a very considerable reduction in the effective insulation of paper cables at telephonic frequencies, especially with heavy conductors, though it is negligible with small conductors.

He finds that for viscous dielectrics $\frac{S}{PK}$ is independent of K

and also of the temperature, at any rate between 0° and 25° Cent.; and that where P = 5000, $\frac{S}{PK} = .018$ or $\frac{S}{K} = 90$.

Nevertheless increase of leakage is in some degree an alternative method of curing distortion in telephone cables, but practically it is essential that all lines, whether cable or open wire, loaded or unloaded, should be kept at the highest insulation point, consistent with due economy.

The practical solution has been reached—

(1). By reducing R.
(2). By reducing K through using air-space paper-insulated cables.
(3). By adding L in the shape of loading coils containing high inductance but small resistance.

LOADED LINES.

The artificial insertion of inductance into telephone circuits has only become a practice in the last few years, although it was shown theoretically to offer advantages by Mr. Oliver Heaviside as far back as 1887.

Since 1891 Prof. Sylvanus Thompson and others have taken out various patents, but it was not until Prof. M. I. Pupin re-investigated the subject in America in 1899 that any practical steps were taken.

PUPIN'S LAW.

Pupin proved that the loading gave the same results as a cable of equal total R and L, but with this R and L smoothly distributed, provided that the wave length extended over at least nine or ten coils at any particular frequency, and provided that the spacing of the coils was regular. His law may be stated as follows :—

Take the wave length as 2π and θ the angular distance between the loads, then the loaded cable will be equal to a cable with smoothly distributed R and L, if $\sin \frac{1}{2}\theta = \frac{1}{2}\theta$ or $\sin \frac{1}{2} \frac{2\pi}{N} = \frac{1}{2} \frac{2\pi}{N}$ where N = number of loading coils per wave length.

The reason is this ; when a current travelling along an uniform conductor arrives at a point at which the inductance or capacity per unit of length suddenly changes, there will be a reflection of part of the wave just as in the case of a ray of light when passing from one medium to another of a different refractive index.

Accordingly loading coils will cause reflections and so diminish the amplitude of the transmitted wave, unless the wave length is large compared with the length of the coil intervals.

Hence if the wave form is complex and it passes over a line loaded with inductance coils placed at intervals—which are short compared to the fundamental wave length, but long compared to the higher harmonic wave length—then the effect will be to stop these latter or filter out the harmonics and let pass only the fundamental sine curve component.

Dr. Hayes later on proved that cables loaded with four or more inductance coils per wave length will transmit telephone wave impulses practically as well as though the inductance was uniformly distributed, but waves with less than three coils will be reflected, so that the attenuation would be very great.

In any case, for less than four or five coils per wave length, the actual attenuation is very much greater than the attenuation calculated on the assumption that the added L and R are smoothly distributed.

THE π LAW.

Various authorities have shown that if a long thin stretched string be taken and loaded with small weights at equal distances, it will vibrate practically as though uniformly loaded if there are not less than π loads per wave length.

Of course, the closer the loads, the shorter will be the wave length which the string will be able to transmit.

Prof. Pupin and Dr. Campbell both recognized an analogy between the behaviour of a loaded string and that of an electrical circuit where the inductance coils at regular intervals take the place of the loads on the string.

Working on this analogy, to obtain sufficiently clear speech for practical purposes, it is essential that waves with a frequency of 2,000 should be transmitted; there must therefore be π coils per wave length at this frequency.

If a loaded circuit approximates to an uniform conductor for waves of a certain frequency, then it will approximate still more closely for all lower frequencies.

Wave lengths decrease with frequency and loading.

This establishes a simple rule, where the inherent inductance in any telephone loop is so small as to be negligible, viz.:—where there are just π coils per wave length and $n = 2{,}000$, $Dik = 25{\cdot}3$.

This represents the worst permissible condition; it is better to allow some margin and take $Dik = 20{\cdot}4$.

Generally, as regards the amount of inductance to be inserted to produce the best results on any given line, there is a certain critical point on every circuit.

Although in perfectly insulated lines, the inductance may be increased almost indefinitely, provided that the resistance is not increased at the same time, yet in imperfectly insulated lines, there

is a limit beyond which an increase of inductance actually increases β instead of diminishing it, *i.e.*, when $L = R\frac{K}{S}$. Experiments indicate that l should not exceed $2r$.

Cables can now be manufactured for loading purposes with such low values of leakance that its influence on β is negligible, and a negligible leakance can also be secured in the inductance coils.

Heavy loading means shorter wave lengths and consequently shorter distances between coils, which entails increased cost for coils, coil pits or test boxes and their maintenance. Each case must be considered on its merits, as to whether it would not be more economical to instal conductors of a somewhat heavier gauge.

The cost of the coils, etc., is usually very much less than the cost of providing an unloaded cable of equal efficiency, and a loaded cable will require less duct space. Efficient working can be secured on underground coil-loaded trunk lines up to 620 miles with conductors no greater than 215 lbs.

SPACING OF COILS.

If the spacing of the coils is such that there are fewer than nine coils per wave length, then the actual β is greater than that predicted by assuming the total R and L as smoothed out, as follows :—

For 8 coils, the actual β	is	greater	by		1	per cent.	
,, 7	,,	,,	,,	,,	2	,,	
,, 6	,,	,,	,,	,,	3	,,	
,, 5	,,	,,	,,	,,	7	,,	
,, 4	,,	,,	,,	,,	16	,,	
,, 3	,,	,,	,,	,,	200	,,	or more.

The more modern rule is therefore—assume the total R and L of line and coils to be uniformly distributed.

Then find α and λ for the average frequency (800) of the speaking voice. If this λ is more than eight or nine times the distance between the coils, calculate β with this R and L smoothed out and the result will be quite near enough to the actual measured or real β.

It is important that the loading points should be regularly spaced, at least within 4 per cent. to 5 per cent., as otherwise some loss results from reflections between them.

If the spacing is increased, but at the same time the amount of inductance inserted per mile is unchanged, β will gradually increase and at one particular spacing it will increase to an enormous extent.

Where physical conditions impose a variation of not more than 50 per cent. of the spacing for a single coil, no appreciable impairment in the quality of speech will result, provided that the deficiency in loading is made up within the next ten loading sections.

A coil practically loads a loop, equal to half the spacing on each side of it, so that the first and last coils should be half the normal spacing distant from the ends; then if two similarly loaded loops are joined in series, the spacing throughout is kept uniform.

In this way terminal losses are also reduced, as this half-normal spacing acts as small terminal tapers, when speaking takes place over the loaded loop only. Terminal losses will be referred to later.

APPLICATION OF FORMULÆ (FOR LOADED LINES).

When the inductance has been greatly increased by the insertion of loading coils, a considerable simplification of the formulæ for α and β is possible.

This does not apply, at present, to "continuous loading." In a properly loaded circuit, PL is much greater than R and in any normal underground or submarine circuit, PK is much greater than S.

Therefore formula (1) for α reduces to (7) and formula (3) for β to (11). Formula (11) indicates a distortionless condition, and is sufficiently true for all inductances between the practical loading limits of ·05 henry to about ·4 henry per mile on lines of negligible leakance.

From formulæ (9) and (10), β and W are both independent of n when L is large compared to R, for moderate frequencies. For very high frequencies, PL tends to be always greater than R under any circumstances.

R and L at different frequencies can be fairly measured, and, their values for the particular frequency assumed, may be inserted in formula (11), but little is known of the variation of S and K with frequency, especially with the dielectrics used in practice.

However at any particular frequency, the ratio $\frac{S}{K}$ will be constant,

i.e., $\frac{S}{PK} = \text{constant}$.

An accurate method of measuring S is given by Ebeling (see Bibliography), but no really satisfactory method has yet been found for measuring K at telephonic frequencies; there is no doubt that $\frac{S}{K}$ plays a very important part in determining speech-transmitting efficiency.

Owing to our incomplete knowledge, K must be assumed to be the same at all frequencies and by a large number of practical experiments, values have been fixed for $\frac{S}{K}$ to agree with observed results.

For loading coils with non-magnetic cores and no magnetic, material near them, $\frac{S}{K} = 50$.

For loading coils with magnetic cores to form a closed magnetic circuit, $\frac{S}{K} = 80$.

The higher potential along a loaded cable has a greater tendency to cause cross-talk, due to the want of balance of the capacity between adjoining pairs and thus a greater precision in cable construction is required to secure symmetry.

It is also more important to preserve better insulation on loaded than on unloaded circuits, since any leakage tends to increase the attenuation, on account of the slower propagation of the waves affording a longer time for leakage at each impulse. The insulation must never fall below 10,000 ohms.

Leakance is only negligible with small conductors, when formula (11) will reduce to formula (9*a*). With the larger conductors the effects of leakance can be lessened by reducing the inductance.

For short lengths of line, loading is not generally considered beneficial, as the added resistance increases the attenuation constant at first more than the added inductance reduces it.

The late N.T.C. however tried two coils on a $3\frac{1}{2}$-mile loop of 20-lb. cable and obtained an improvement of 184 per cent.; and further experiments indicated that one coil in a 2-mile length would improve the efficiency by 120 per cent. to 200 per cent.

In practice generally, an improvement up to 370 per cent. can be obtained by loading cables with coils, but it is always greater for the smaller conductors.

To summarize, the loading effects five great improvements :—

(1). It increases the value of the propagation constant, both as regards size and slope.
(2). It reduces the value of the attenuation constant (β).
(3). It reduces the wave length (λ) for a given frequency (n) and also the wave velocity (W).
(4). It gives the cable a larger initial sending end impedance and therefore reduces the current in the cable with a given impressed voltage.
(5). It tends to unify or equalize the attenuation constants and also the wave velocities for different frequencies. The lack of complete equalization is due to the increase of effective resistance of the coils with increase of frequency.

The result is that the wave form is propagated not only with less attenuation, but with less distortion or loss of individuality, owing to the more equal attenuation and velocity of the various harmonic constituents.

It is interesting to note that the late N.T.C., even with their short lines, had 2,500 miles of loaded circuits, while in the U.S.A. there are 170,000 miles of loaded buried circuits.

Description of Coils.

There were till recently two kinds of coils :—

(1). Without non-magnetic core, *i.e.*, air-core (cylindrical type).
(2) With magnetic core of iron wire, *i.e.*, iron-core (ring type).

Every air-core coil, which pattern is now obsolete, had an external magnetic field ; consequently there were the following disadvantages :

(i.). Eddy currents, set up in any metal in the vicinity by reaction increased the effective resistance of the coil and reduced its efficiency.

(ii.). A case of four coils was arranged so that they were normally free from inductive disturbances, one with another ; but if this case was placed near a mass of iron, the conditions became different and overhearing occurred between all of them.

(iii.). Two similar cases of coils could not be placed near to and parallel with each other without the coils of one being parallel with those of the other. Overhearing therefore ensued between the circuits passing through the coils in the two boxes.

(i.). and (ii.) could not be overcome.

(iii.) was overcome by making two types of case, in which the coils in one case were at right angles to those in the other. These were arranged alternately not less than 4 in. apart.

Also (iv.) the effective resistance for a given inductance was high.

(v.). It was difficult to keep the cases air and watertight as they could not be enclosed in an iron case and consequently the insulation of the cable was bad.

(vi.). Air-core coils were bulkier than iron-core coils for a given inductance.

Iron-core coils, being wound on rings of magnetic material have negligible external fields. Therefore, provided a thin shielding plate be placed between them as a precaution against electrostatic or slight electromagnetic effect, they may be placed one on another to any extent and enclosed in a watertight iron case. Moreover they possess a much higher inductance than air-core coils for a given effective resistance. They have one disadvantage however :—If a current, say ·15 ampère, which is large from a telephone point of view, is passed through the circuit while testing, etc., the cores are liable to become permanently magnetized, not being pure iron, in which case the inductance is lowered and the effective resistance increased.

This is not serious as one or two applications of the following treatment will readily remedy it :—

Apply a relatively strong alternating voltage to the circuit so as to cause a current of ·2 virtual ampère to flow. Then by inserting resistance in the loop, gradually reduce the current to less than ·001 ampère.

As regards quality of speech, iron-core coils prove just as efficient as air-core coils. Iron-core coils will undoubtedly be the loading coil of the future, though at first, while they certainly increased the volume, they were found to impair the articulation.

In well-constructed loading coils the effective resistance is about 6 ohms for every 100 millihenries of inductance at a frequency of 750 ; in America they have used coils for some years past on aerial lines with an effective resistance of only 3 ohms per 100 millihenries.

The resistance varies from 3·5—18 ohms with inductance varying from ·05—·4 henries at frequency 1,000 for the different sizes of coils ; the maximum time constant $\left(\frac{L}{R}\right)$ at speech frequencies is ·022.

The diameter overall is $4\frac{1}{2}$ to 10 in., and the depth 2—4 in., while there is also a hole in the centre of $1\frac{1}{2}$—2 in. diameter.

These coils are undoubtedly the best means of loading a telephone cable where the cable is long and where high technical skill is available, both for the fitting of the coils and their subsequent maintenance ; but in other cases they are not to be recommended if any other method can be adopted.

CONTINUOUS LOADING.

This is generally effected by covering each conductor of the loop with one or more layers of finely-drawn iron wire or strip.

This method has several disadvantages compared to a non-uniformly loaded cable, viz. :—

(1). It is about twice as expensive.

(2). It is not possible to predict β with any certainty, on account of the unknown permeability of the iron wire, especially after winding on, which hardens it and so tends to decrease the permeability, and also on account of unknown increases in effective resistance due to hysteresis and eddy currents.

(3). It increases the duct space required since the overall diameter of the conductor is increased.

(4). In a multi-core loaded cable, all the cores may not require loading at first. In a continuously loaded cable, no change can be made after laying.

Little practical experience has been obtained on actual circuits in this country, but some laboratory tests have been made which showed a great increase of resistance and about 200 per cent. increase in capacity.

Calculation and observation differ widely and is receiving further investigation.

The British Insulated and Helsby Company have made a considerable number of experiments, resulting in the construction of an air-space cable for Sir John Gavey which gives very satisfactory tests.

This cable is of 100-lb. copper, lapped with two layers of a very soft iron tape $\frac{1}{100}$ in. thick and $\frac{1}{10}$ in. wide; the hardening produced by winding has been removed by thorough annealing.

Tests give the following constants :—

$k = \cdot 059.$
$l = 17.$
$R = 22 \cdot 4$ at frequency 800.
$\rho = \cdot 0207.$

The calculated improvement was 103 per cent., but the actual value is found to be well over 130 per cent. on a length of $47\frac{1}{2}$ miles.

Since the iron strip or wire increases the diameter of the conductor, it is necessary to correspondingly increase the overall diameter of the cable to prevent a rise in the capacity, but the B.I. Company are now able to continuously load cables in such a way that this increased overall diameter is not a very serious matter.

Given a knowledge of the magnetic properties of the lapping of iron and annealing after hardening, the ordinary Pupin formulæ will then apply.

The winding of the iron not only decreases its permeability but certainly increases also the hysteresis.

An improvement of 100 per cent. can now be obtained at an extra cost of 50 per cent. by using iron equal to half the weight of the copper; more iron than this will do harm, less may perhaps be better; the problem is one for higher mathematicians.

The advantages of continuous loading are as follows :—

(1). The cable, after it leaves the factory can be handled exactly like an ordinary cable.
(2). It requires no more attention for maintenance than an ordinary cable after it is laid.

The best effect will be where a long aerial line is interspersed with short lengths of cable, such as through railway tunnels, from an exchange to meet overhead trunk lines on the outskirts of a town over bridges, across rivers and in all cases where a highly skilled staff is not available for laying and maintenance

The problem of "coil" *versus* "continuous" loading is now practically one of finance only.

Formulæ for calculating the inductance and eddy current and hysteresis losses in continuously loaded circuits are given in Appendix VIII. of Major O'Meara's paper on Submarine Cables published by I.E.E. in April, 1911.

REED-THOMPSON CABLES.

Mr. Reed and Prof. Thompson both proposed in 1893 to cut up a cable into sections inductively connected by transformers. Dr. E. F. Roeber proved mathematically that this arrangement is equivalent to placing loading coils in series, but with the centre point of each coil connected by another coil to the centre point of the coil opposite to the first one on the other wire of the circuit, and that it was equivalent to an uniform line, provided that the transformer intervals were short compared to the wave length, exactly following Pupin's law.

Prof. Thompson also proposed about 1893 to insert loading coils in parallel, but recent experiments have proved that for a given amount of iron and copper in the form of impedance coils, this method gives a greater attenuation constant than when the coils are in series.

The attenuation also varies with frequency to a serious extent and great distortion occurs as well, so that this method is unlikely to be adopted in practice.

BUNCHING.

Cables of the multiple-twin and quad.-pair type make possible the bunching of two or more pairs of wires to form one circuit free from inductive disturbance, but there is, as a general rule, a decrease in efficiency.

In the case of two 100-lb. cores joined in parallel, a gain of 25 per cent. in efficiency is paid for by an increase of 100 per cent. in the cost of the copper. Four pairs in parallel are 50 per cent. worse than a single pair.

A large part of this loss is due to the capacity having been increased at the same time, which is more unfavourable than is compensated for by the increased weight.

There is no advantage for transmission purposes in bunching wires in cases where the capacity is doubled and the resistance halved, as may happen in small cables (see formula (6)).

Bunching will as a rule only be found advantageous on subscribers' circuits not exceeding 5 miles in length, as the effect of increased capacity is negligible and these circuits are governed by ohmic resistance only, since the transmission allowance is dependent on the central battery feeding current.

LOADING AERIAL LINES.

The improvement gained by loading aerial open lines is small compared with that on underground circuits, and is due to the greater conductivity, the higher inherent inductance and the lower capacity of aerial wires. Initially, open wire circuits are practically free from distortion, while the want of loudness in the received sounds is chiefly due to the resistance of the line. The leakage trouble is a disadvantage in this country.

In America with its drier climate, loading aerial wires is considerably practised and there are now 85,000 miles of loaded open circuits in the U.S.A., but a more efficient type of glass or porcelain insulator has had to be substituted, to keep down the leakage. Leakage is more important with the heavier lines; the insulation resistance on loaded aerial lines must be 2 to 3 megohms per mile against the present standard of 200,000 ohms per mile for unloaded wires. Germany has also tried loading aerials with success and they find that a loaded 215-lb. circuit is equal to an unloaded 500-lb. line.

The coils are best not placed on the top of poles, where they run the risk of damage by lightning, but they should generally be fixed in test boxes or pillars. In practice, the smaller gauges of wire can be improved 200 per cent. by loading.

PHANTOM CIRCUITS.

"Phantom" is the very apt term used in America to describe a superimposed circuit, *i.e.*, an additional circuit superimposed on two existing separate circuits by means of transformers or bridging coils.

Phantom circuits have a higher transmission efficiency after a certain distance than the circuits in pairs of the same gauge.

Experiments have been made with success to superimpose a further circuit on two phantoms, and it is called a "ghost" circuit. It is thus possible to obtain seven circuits out of four pairs.

Between two military exchanges at Portsmouth, five pairs of junction lines have been obtained from three pairs of aerial wires, one pair of which even runs on a different route to the other two and the arrangement is working perfectly.

Mr. Carty proved that a phantom circuit can also be loaded.

Communication is now possible between New York and Denver, a distance of 2,011 miles. It consists of aerial open 435-lb. wires throughout as follows:—

New York—Chicago by phantom on two pairs.

Chicago—Omaha on one pair (to be altered to phantom).

Omaha—Denver by phantom on two pairs.

The phantoms themselves are loaded; special loading coils are used on the side circuits and also on the phantom circuits.

The possibility of telephoning between New York and San Francisco, 3,000 miles, is now under consideration.

The Boston-New-York-Washington underground cable line, 475 miles long, is nearly completed. This cable is so constructed that practically all the circuits in it may be phantomed and so that these phantom circuits, as well as the side circuits of which they are made up, can be loaded.

It consists of 14 pairs of No. 10 B. & S. gauge 36 ,, ,, 13 ,,	Quadruple pairs and can be phantomed, giving 25 extra circuits.
6 ,, ,, 13 ,, 18 ,, ,, 16 ,,	Twin pairs.

The phantomed No. 10 wires will be the only ones of commercial use for speaking between Boston and Washington.

The loading coils are spaced at intervals of about 1—4 miles, the side circuit coils and phantom coils being placed at the same point.

The side circuits have a mutual capacity of about ·070 mfd. per mile, while that of the phantom is about ·1 mfd. per mile.

Extensive use has also been made of means permitting the simultaneous use of a line for telephony and telegraphy.

If the two wires of a telephone circuit are used in parallel as a telegraph circuit, the line is " simplexed."

If the two wires are used for independent earthed or grounded telegraph circuits, the line is " composited."

The compositing of a circuit does not limit the possibilities of also using it as one side of a phantom.

The transmission loss due to the addition of composited apparatus to the two ends of the circuit is just noticeable, being about one M.S.C.

The loss due to simplexing depends on whether bridging coils or transformers are used. In the case of small cheap transformers the loss may be as much as 6 or 7 M.S.C. The best type give a loss of 2 M.S.C. for the side circuits, but the loss is negligible in the phantom.

It is always cheaper to use the more expensive transformers which produce little loss, than to use cheap apparatus and have to make up its loss by a larger gauge of conductor.

For further information see the *National Telephone Journal*, July—October, 1911.

STANDARD CABLE.

There are several methods by which the transmission efficiency of a telephone circuit may be measured, but the most satisfactory so far is that known as " Standard Cable Equivalents (S.C.E.)."

By this method, a length of cable, the electrical and attenuation constants of which are known, is arranged with a change-over key

so that equal volume or loudness of speech is received from the same instruments through it and the circuit under test.

The transmission in these tests is a repetition of the numbers 1, 2, 3, 4, 5, spoken successively.

The standard cable equivalent of any telephone loop may therefore be defined as the length of standard cable having the same telephonic transmission efficiency as the loop under test.

The standard apparatus generally used is of the common battery type with solid back transmitter and constant voltage from accumulators, but, as the tests are comparative only, there is no reason why primary battery instruments, though less efficient, should not be used as standards for W.D. requirements.

The cable used as a standard is called "Standard Cable" and in England consists of a 20-lb. copper conductor, 20 S.W.G., diameter 36 mils., air-space, paper-insulated, loop circuit, enclosed in a lead sheath and possessing the following constants :—

$r = 88$ ohms.
$k = \cdot 054$ mfds.
$L = \cdot 001$ henries.
$S = 5 \times 10^{-9}$ mhos.

Measurements made at 60° F.

(=insulation resistance of 200 megohms).

Whence $\beta = \cdot 103$ at frequency 750.

If P is taken as 5,000, which is more usual, $\beta = \cdot 107$, $\alpha = \cdot 111$, $W = 44{,}900$ and $\lambda = 56 \cdot 6$ miles. The attenuation constant of this cable has been verified by many practical experiments and its commercial speaking limit is 43—46 miles, but the expert range is 50—60 miles.

If the S.C.E. of a circuit is known, it is easy to deduce its β, *e.g.*, a certain loop 70 miles in length is found to be equivalent to 20 miles of standard cable (M.S.C.).

$$\therefore \quad \beta = \cdot 107 \div \tfrac{7}{2}^{0} = \cdot 03 \text{ nearly.}$$

Artificial cables, calibrated against an actual standard cable, are mostly used in practice for testing purposes. They are generally constructed to give any value between 1 and 60 miles of standard cable by 1-mile steps ; it is desirable to be able to put about 10 M.S.C. in circuit at each end when testing short lengths of cable, to eliminate terminal effects ; it is also an advantage to have the instrument fitted so that telephone sets can be tested against the standard ; for this purpose two extra change-over keys and sections of $\frac{1}{2}$ and $\frac{1}{4}$ M.S.C. are added. The resistance and inductance are generally placed half on each leg in series and the capacity in leak. The condensers used for the capacity are constructed with silvered mica plates instead of paraffin-waxed paper to prevent the capacity decreasing with the

high-frequency currents and to minimize the effects of temperature. The set complete costs about £50 and is fairly portable.

With practice, variations of very small fractions of a mile can be detected, and when used by experts it is accurate to within 5 per cent.

The method of "standard cable equivalents" can only be carried out when there are two or more pairs of wires in the cable or line under test. When the line contains only one pair, the attenuation constant can be calculated or it can be deduced from current measurements which are mentioned later.

It is usual to measure as many different lengths of the same type of loop as possible and then plot a graph, which as a rule works out as a straight line.

In a cable containing many pairs, such different lengths may readily be obtained by joining the loops in series, to and fro, in the cable; care being first taken to prove that there is no inductive disturbance between the pairs so joined in series.

The method of S.C.E. is of course founded on a purely arbitrary basis and has no direct relation to the C.G.S. system, but on the other hand, β is based on the C.G.S. units.

Some attempt has therefore been made to introduce a practical unit, such as the "centibeta" to express transmission efficiency. The limit of 46 miles of standard cable might then be expressed as $46 \times \cdot 107 \times 100 = 492 \cdot 2$ centibetas, but so far it has not met with much success.

IMPEDANCE METHOD.

It is possible that the "impedance method" may be introduced, *i.e.*, the method of comparing efficiencies by means of the total impedance of the circuits.

MEASURING INSTRUMENTS.

The *Oscillograph* invented by Mr. W. Duddell, F.R.S., is used for studying telephonic waves, but the measurement of frequencies from its diagrams is very complex and laborious.

The *Thermo-galvanometer* by the same inventor is used for measuring the minute telephone currents and to test the electrical constants of loading coils with high-frequency currents. It has many advantages, and for deflectional methods is unrivalled if the source of power is absolutely steady; it cannot therefore be used with transmitters, even though the sound impressed on the transmitter is steady.

Considerable difficulty has been experienced in obtaining an alternator to give a steady sinusoidal current of the frequencies required for telephonic measurements, but a wave filter has been invented to sort out the upper harmonics.

It consists of double-wound loading coils of ·17 henry each, the two

coils assisting each other and across the junctions are placed condensers of $\frac{1}{4}$—$\frac{1}{2}$ mfd. There is also some non-inductive resistance in series, making the filter more abrupt.

Baretter.

The Baretter or Bolometer, improved by Cohen, is used for :—

(1). Measuring the impedance of any piece of telephonic apparatus expressed in ohms for any type of alternating current.

(2). By employing an alternator giving a simple periodic or sine form E.M.F., the actual inductance, effective resistance and capacity of any piece of apparatus for these high-frequency currents can be measured.

(3). Small alternating currents can be measured with an ordinary galvanometer.

(4). The direct comparison of various types of cables with the standard cable can be made.

It consists of a conducting wire or filament, which has a high temperature co-efficient and small mass, so that small currents will appreciably raise the temperature and thus alter its resistance. Kennelly used very fine platinum wire, but that was found too delicate ; Hayes used a switchboard carbon lamp and the late N.T.C. a special pattern of 24-volt curl filament carbon lamp, originally designed for switchboards.

Wheatstone's Bridge.

Inductance and capacity may also be measured on the lines of a Wheatstone's Bridge, where an alternator replaces the primary battery and a telephone receiver the galvanometer, comparisons being made against a known standard inductance or capacity.

A.C. Potentiometer.

For measuring very small voltages, there may be used an alternating current potentiometer, such as the Drysdale-Tinsley form. This instrument consists of a standard form of potentiometer as used for D.C. work, but it is supplemented by means for passing through the standard wire an A.C. of known value derived from the same source as the potential to be measured, and also with means for shifting the phase of this current and changing its amplitude. This phase shifting is accomplished by Drysdale's phase-shifting transformer

Wattmeter.

Dr. Sumpner's Wattmeter is used for measuring capacity, especially where it is necessary to separate out the true conduction current from the true dielectric current.

For further information on all the above instruments, see Fleming's *Propagation of Electric Currents* and Kempe's *Electrical Testing*.

The average voltage in a loaded cable is maintained at a higher value than in an unloaded circuit. The principal losses of energy in the dielectric are due to residual charges. Such losses vary with the square of the voltage, so that, when making measurements with alternators, it is necessary to keep the impressed voltage down to the order of telephonic currents.

TRANSMISSION STANDARDS.

The telephone agreement of 1905 between the P.O. and N.T.C. was based on common battery working and affords a standard for all future serious telephone work in this country. The "test instruments" mean C.B. apparatus fed by a battery of 22 volts through an external line resistance of 300 ohms; the sending allowance is 8·1 M.S.C. and the receiving allowance is 1·2 M.S.C.

Primary battery instruments with hand telephones about equal "test instruments" in efficiency.

(1).—(*a*). For subscribers' circuits on the same exchange or on two different exchanges in the same exchange area, where the radial distance between the two exchanges does not exceed 10 miles, the standard of speech shall not be inferior to that afforded by test instruments connected by a length of 20 M.S.C.

(*b*). If two subscribers are each more than 5 miles from their exchange, the above limit is increased to 25 M.S.C.

(2).—(*a*). Where the radial distance between the exchanges is between 10 and 50 miles, the limit is 30 M.S.C.

(*b*). Similarly, if as in (1) (*b*), the limit is 35 M.S.C.

(3). (*a*). For subscribers' lines plus junctions to P.O. trunk exchange, in the same exchange area, the limit is 5 M.S.C.

(*b*). If the radial distance between the subscriber and the Trunk Exchange exceeds 9 miles, the limit is increased to 8 M.S.C.

The latter case would limit any made-up trunk line to a S.C.E. of 30 M.S.C., but of course in practice two subscribers' circuits plus two junctions would rarely attenuate as much as 16 M.S.C.

The effect of local wiring, cords, etc., in an exchange may be taken to have a S.C.E. of $\frac{1}{2}$ to 1 M.S.C.

A table of transmission equivalents for various types of circuits is given at the end.

Terminal Losses.

Terminal losses suffer from peculiar variations and have not yet been sufficiently investigated.

The loss however may be reduced in several ways :—

(1). By " tapering," *i.e.*, reducing the inductance in each coil at the ends of the circuit, but it is counterbalanced by the consequent reduction of efficiency of the loading generally, and necessitates further alterations if another length of loaded cable is added at either end. It is not likely to be used in the future.

(2). By extending the loaded portion with artificial resistance and capacity at each end, and, by making these latter sufficiently high, all terminal loss may be removed, but this combination has as great a S.C.E. as the terminal loss, so no benefit results.

(3). By terminating the loaded loop through one coil of a specially designed transformer at each end, the telephone set being joined to the other transformer winding. Great complexity is entailed by this method and it can be dispensed with when terminal circuits are of moderate or greater length.

(4). Most loaded lines are subject to extension by actual unloaded loops, and so the terminal loss automatically disappears.

Prof. Fleming and Dr. Hayes state, however, that reflection is considerable when short loaded sections are joined to unloaded sections, and that its effect on the attenuation may be reduced by decreasing the added inductance.

The nearer the first and last coils are to the ends of the circuit, the greater is the terminal loss, but this can be considerably reduced by spacing the first and last coil at half the normal spacing from the ends.

Reflection can be neglected in practice on unloaded circuits :—

(1). If the lines are short, comparisons with standard cable are difficult and the terminal effect swamps the effect of the line. On a loop of 4 miles of 20-lb. cable, the S.C.E. really has a negative value ; it would however not be observed by the aural method of comparison. It is quite easy to put in artificial cable at each end to eliminate these effects, when testing.

(2). If the lines are long, the line impedance is large in comparison with the loss due to reflection at junctions, and the effect is not felt.

(3). If the sections of cables interspersed with open wires are short, reflection is negligible.

Any apparatus introduced into the circuit gives rise to impedance and, to a certain extent, reflection. Campbell has shown that, if its impedance equals that of the line, there will be no loss due to reflection.

MIXED CIRCUITS.

So far as measurement by S.C.E. method shows, there is no loss due to joining loaded and unloaded lines of any type in series in any order.

Take for instance :—

	S.C.E.	
(*a*). Aerial loop	12·6	M.S.C.
(*b*). Underground loop unloaded ..	7·5	,,
(*c*). Underground loop loaded + terminal loss of 5·8 M.S.C.	14·8	,,
Total	34·9	,,

Join (*a*) (*c*) (*b*) in this order, then the observed S.C.E. from either end (*a*) or (*b*) is 29 M.S.C., showing that the terminal loss has been wiped out.

Join (*a*) (*b*) (*c*) in this order, then the S.C.E. from (*a*) end is 29 M.S.C. as before, but from (*c*) end it is 31·9 M.S.C., because of the terminal loss at this end.

It has been exhaustively proved that, excluding terminal loss on loaded lines, the S.C.E. of any number of different loops joined in series in any order is equal to the sum of the S.C.E.'s of the parts measured separately.

If it is desired to furnish transmission between points 400 miles apart, of which 10 miles must be cable, it would be uneconomical to use a large open conductor say 400 lb. and a 10-lb. cable ; it would probably be better to use a 200-lb. aerial and a 150-lb. cable.

G.P. AND S.M. CABLES.

Although doubtful up to recent times on account of the low effective insulation to currents of high frequency, cables insulated with G.P. follow the same laws as paper-insulated cables and aerial lines, etc., provided that the G.P. is kept wet, because the effective insulation resistance of G.P., when dry, is variable and lower in value.

As long as the insulation resistance is practically constant for the whole length, it does not matter as regards transmission efficiency, whether its value is 1 megohm or 500 megohms per mile.

With reference to formula (11), the value $\frac{K}{L}$ is by no means negligible in practice, when inductance is introduced. Hence leakance tends to increase attenuation.

Cables insulated with G.P., which has a low dielectric resistance, have therefore a relatively large attenuation constant.

This large value of S does not as a matter of fact, however, nullify the effect of any loading by inductance.

If the insulation resistance was infinite, β could be reduced 50 per cent., which is the minimum value possible without reducing the effective resistance of the coils below 6 ohms per 100 millihenries.

G.P. cables are only half as efficient as air-space paper cables.

Certain types of G.P. cables are known to be characterized by considerable true leakance as well as capacity, *i.e.*, the G.P. as a dielectric has a true conductivity, perhaps owing to moisture present in it, as well as dielectric quality.

Hence many of the methods proposed for measuring capacity do not give correct results with G.P. cables.

"*Drumminess*" is a property of G.P. cables which causes speech to be muffled. In unloaded cables it is generally unmistakable when $\frac{k}{r} = \cdot 003$ or over, *i.e.*, it is affected by the relation of the weight of the G.P. to the weight of the copper conductor per mile.

Drumminess is largely caused by the unequal attenuation of speech waves of different frequencies and the undue preponderance of some particular tone, coupled with the fact that speech waves travel with different speeds according to their frequencies. Commercial receivers are not designed for use on one type of circuit, but for general all-round use.

A low value of β can be obtained without any loading at all by making the conductor large enough and the dielectric thick enough, but it produces drumminess which can only be got rid of by loading with inductance.

A S.M. cable is not as efficient after loading as the same gauge of unloaded conductor in a land line; it is therefore better to increase the size of the land conductors joined to it.

If loading is necessary, not only to get the maximum improvement but also to get rid of drumminess, it is preferable to have a greater proportion of copper to G.P. as it effects the maximum gain with less added inductance, which means fewer coils and wider spacing; the results are therefore in favour of light conductors heavily loaded than heavy unloaded wires.

Mechanically spaced loading in S.M. cables involves greater risk in the usual operations ; the cable is less simple to manufacture and handle than a continuously loaded cable.

The insertion of coils in aerial lines at poles or in buried lines at test boxes is a comparatively simple matter, but it is not so simple to insert isolated coils in S.M. cables so that all the exigencies attending cable operations can be satisfactorily met. Continental engineers have kept to continuous loading, possibly reckoning the additional efficiency of spaced loading not worth the mechanical difficulty and risk involved ; such cables have been insulated with either G.P., solid paper, air-space paper or impregnated paper.

A coil-loaded paper cable is laid across Lake Constance. Generally speaking, G.P. is the only suitable dielectric for S.M. cables that are continually suffering damage from vessels or laid in deep water exceeding 100 fathoms in depth where the pressure would injure an air-space paper cable by compression of the cores, notwithstanding the greater capacity and higher cost of G.P. as a dielectric.

An air-space type of G.P. S.M. cable was introduced to the P.O. in 1897 and tried between Stone Point and Gurnard Bay, I.W., a distance of 2 knots ; this type was then adopted for the extra cable laid from North Wales to Ireland in 1898, but it proved a failure, chiefly owing to manufacturing difficulties in making the four wires at any cross section form a true square.

It was followed by a suggestion to use paper insulation protected with G.P. but the hygroscopic qualities of the paper would cause it to absorb moisture from the G.P., quite apart from the question of the probable high cost of maintenance that a cable, in which paper is used, may involve.

A practical example may be taken in the Anglo-French cable (20 knots) laid in 1910. It is 4-core, 46-lb. copper conductor, insulated with G.P. weighing 116 lbs. per knot ; in later cables there is more copper and less G.P., thus reducing the cost.

The constants unloaded are :—

$r = 14{\cdot}90$ ohms per nautical mile of loop.
$k = {\cdot}138$ mfds. ,, ,, ,, ,,
$L = {\cdot}002$ henry ,, ,, ,, ,,
$S = 2{\cdot}4 \times 10^{-7}$ mhos ,, ,, ,,

Taking $n = 750$, $\beta = {\cdot}052$ calculated from formula (3).

The loading problem was solved by Messrs. Siemens Bros. & Co. as follows :—The two double coils required, each of 6 ohms and 100 millihenries at frequency 750, are inserted at intervals of 1 knot (1·153 miles), but the two coils nearest the ends are only half a knot from the terminal apparatus, to reduce reflection losses. Each double coil consists of two windings on the same iron core and one winding is in series with each conductor.

By this means the gradual change in permeability in the iron core due to ageing will not affect the balance in the two limbs of the telephone circuit. Each coil is protected with a sheet of metal foil to exclude all possibility of the silk covering of the wires of the coils absorbing moisture from the cylindrical envelope of G.P. in which they are contained. The cores of the cable are connected to the envelope at its two ends by tapered solid G.P. joints. The diameter at the centre of the envelope is 3 in. and at the ends 1 in. An annular rubber distance piece is inserted between the two coils of a set to give greater flexibility. The total length of the joint is 30·75 in. As the diameter of the cable at this point is increased, a larger number of sheathing wires are required than over the conductors alone. This difficulty is ingeniously overcome by a second layer of sheathing wires, starting 27 ft. on either side and worked into a single layer over the bulge.

The measured value of β was ·0166 and the improvement due to loading is nearly 220 per cent.

The cost of the cable was £284 per knot approx.

Another cable was successfully laid by s.s. *Faraday* between St. Margaret's Bay and La Panne (Belgium), 47½ knots, on August 23rd, 1911. It consists of four 160-lb. copper conductors insulated with 150-lb. G.P. and is coil-loaded similar to above, whilst provision has been made in addition for a third circuit superimposed, also loaded.

The latest Anglo-French cable was made by the Telegraph Construction Maintenance Co. for the French Government and laid on February 9th, 1912. It is 4-core, 300-lb. composite conductor consisting of a central copper core helically wound with five copper tapes. The loading is a continuous helical winding of ·012-in. steel wire. Each conductor is covered with G.P. to a total diameter of ·412 in.

With $n = 1{,}000$, $\beta = ·018426$ per nautical mile of loop (measured value).

Formulæ (12) and (13) are of very little use as they refer to single wire values of the constants and do not allow for terminal losses which are important and require less added inductance.

REPEATERS.

The invention of an effective telephone relay or repeater is a fundamental problem still awaiting solution.

Two problems are really contained :—

(1). A device for amplifying weak telephone currents without distorting them.

(2). An arrangement of circuits which will permit repeating both ways without switching.

A repeater which is said to accomplish both of these objects has been employed on the long lines of the American Telephone and Telegraph Company for about six years and improves the transmision by 100 per cent.

In this country at any rate it is still in the experimental stage, and owing to its inherent physical characteristics it has, at present, decided limitations :—

(*a*). It cannot be used on a loaded line.
(*b*). It introduces a certain amount of distortion.
(*c*). It is peculiarly susceptible to conditions of line balance.
(*d*). It is unreliable and " sings."

As regards loud-speaking telephones generally, these are still more or less experimental ; it is really a matter of (1) using a fixed transmitter instead of a hand set, to enable the person conversing to speak closer to the transmitter ; (2), improving the microphone capsule ; (3), using more battery power ; (4), improvements to receiver by a better magnetic circuit.

CONCLUSION.

Compared to the design of power transmission systems, there are two main difficulties :—

(1). The problems involved in the case of the telephone are more complex.
(2). The telephone apparatus of different manufacturers is not classified in a standard manner with respect to performance, while power apparatus, such as generators, motors and transformers is rated in definite units as to efficiency, output, etc.

In the design of any telephone system, the provision of a given grade of transmission is now a definite possibility and its provision by the most economical means is one of the more important points in the whole range of telephone engineering.

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The author is indebted to most of the above for many extracts.

TABLE OF TRANSMISSION EQUIVALENTS BASED ON ATTENUATION.

Relative Efficiencies of Various Cables.—Air-space paper, 100. Dry-core solid paper, 80. Impregnated solid paper, 67. Gutta-percha, 50. Rubber (no figures available).

Type of Circuit.	Constants per Mile of Loop.				S.C.E. = No. of Loop Miles giving equal transmission to 1 mile of 20-lb. Cable.	Reciprocal of S.C.E. Multiplier to reduce to S.C.E.
	r ohms.	k micro-farads.	L henries.	S mhos		
P.C. Cable.						
STANDARD { AMERICAN / BRITISH } ..	88	·054	·001	↑	1·0	1·0
10 lbs.	175·64	·07	·001	—	·61	1·64
20 ,, ...	86	·055	·001		1·0	1·0
40 ,, ...	42	·056	·001		1·47	·68
70 ,, ...	25	·063	·001		1·83	·55
100 ,, ...	17	·058	·001	negligible	2·45	·41
150 ,, ...	11·7	·065	·001		2·95	·34
200 ,, ...	8·75	·07	·001		3·5	·29
200 ,, bunched 100 lbs.	9·0	·0846	·001	—	2·8	·35
400 ,, ,, ,,	4·5	·108	—	↓	3·5	·29
Submarine Cable.						
160 lbs. copper and 300 lbs. G.P. per naut. ..	12·9	·12	·00165		2·3	·44
G.P. Quad. Cable.						
40 lbs. copper ..	43	·128	·001		·95	1·1
Aerial Lines.						
40 lbs. bronze ..	90	·00750	·0042	↑	2·83	·35
70 ,, ,, ...	52	·00786	·004		3·9	·26
100 lbs. copper ..	18	·00808	·0039		8·45	·12
150 ,, ,, ...	11·9	·00839	·00376		11·7	·086
176 ,, ,, ...	10·26	·008218	·00370		13·1	·076
200 ,, ,, ...	9	·00862	·00366		14·7	·068
300 ,, ,, ...	5·86	·00893	·00355		21·0	·048
400 ,, ,, ...	4·5	·00919	·00344		26·1	·038
425 ,, ,, ...	4·08	·008978	·00340		27·0	·037
600 ,, ,, ...	2·97	·00958	·00331		36·8	·027
800 ,, ,, ...	2·25	·00987	·00322	↓	45·8	·022

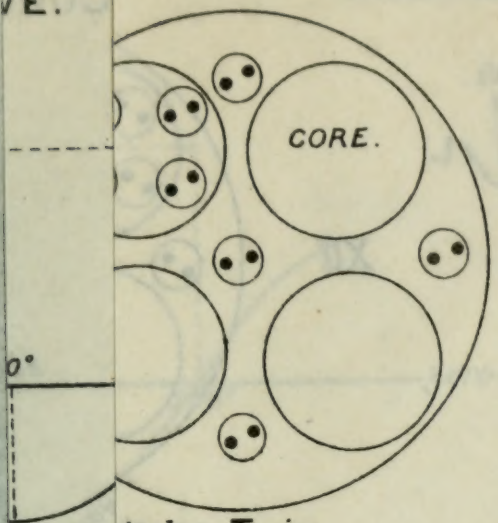
variable, taken as 10^{-6}

In cables up to 40 lbs. where L and S are negligible S.C. equivalent $= \frac{2 \cdot 18}{\sqrt{k \times r}}$.

Commercial speech can be obtained over any line where $\beta \times$ length of loop $= 4 \cdot 8$.

...uple Pair.

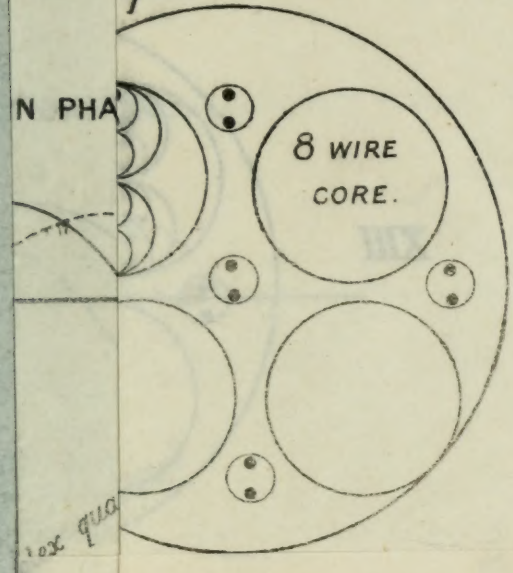
...VE.



...orm.

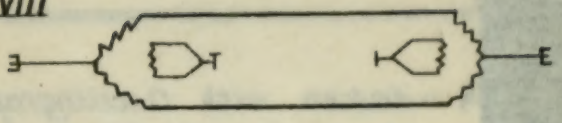
...uple Twin.

...N PHA

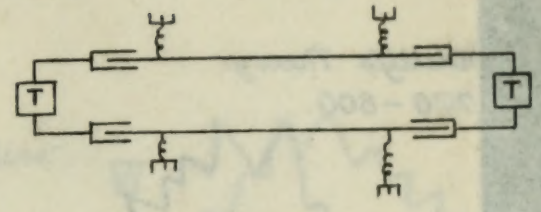


SIMPLEX.

XVIII

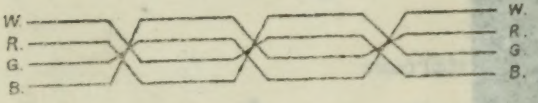


XIX COMPOSITE.



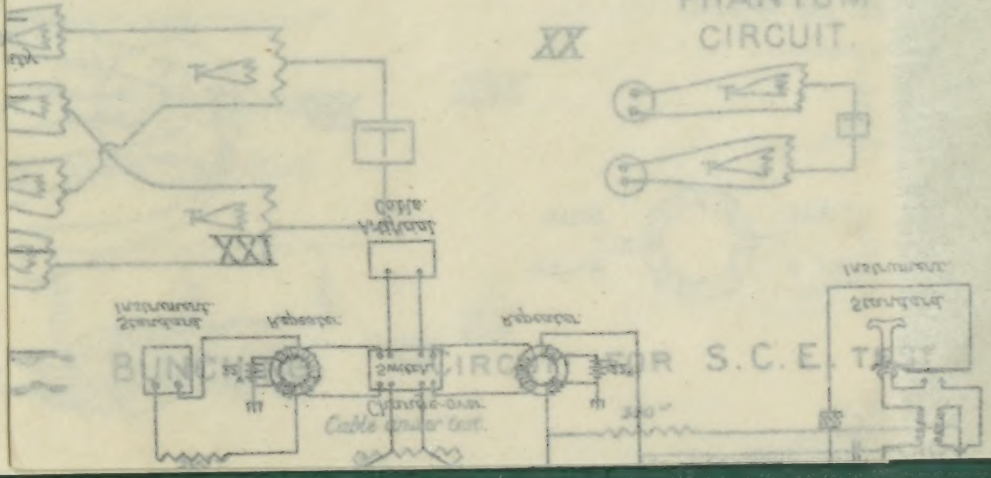
JOINTING.

WHITE	GREEN.
RED	BLUE.
GREEN	RED.
BLUE	WHITE.



...d CIRCUITS (7 out of 8 wires).

XXI

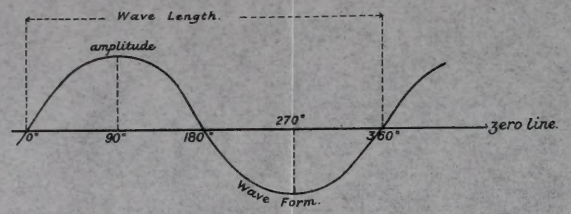


XX PHANTOM CIRCUIT.

TELEPHONE TRANSMISSION DIAGRAMS.

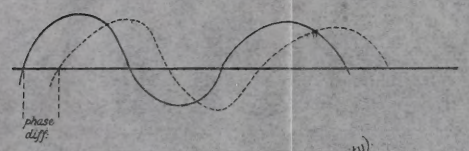
SIMPLE SINE CURVE.

I

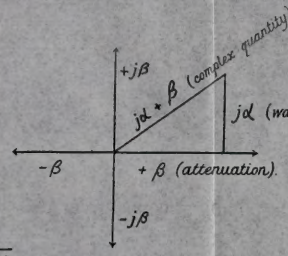


SINE CURVES DIFFERING IN PHASE.

II

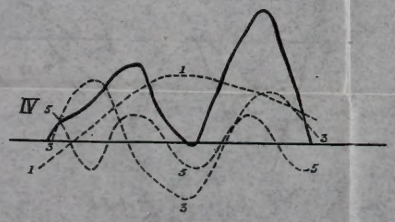


III



$j = \sqrt{-1}$

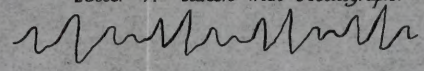
IV



FOURIER ANALYSIS OF A PERIODIC CURVE.

Letter A taken with Oscillograph.

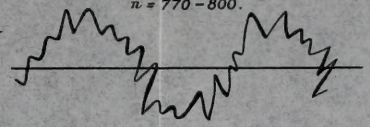
V



Dr. Kennelly's Theory.

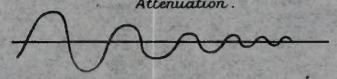
$n = 770 - 800$.

VI



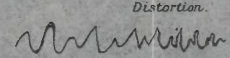
Attenuation.

VII



Distortion.

VIII



PUPIN'S LAW.

IX

Take wave length = 2π

and θ = angular resistance between loads.

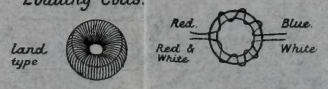
Then loaded cable = smoothly distributed cable

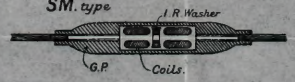
if $\sin \frac{1}{2}\theta = \frac{1}{2}\theta$, or $\sin \frac{1}{2}\frac{2\pi}{N} = \frac{1}{2}\frac{2\pi}{N}$

where N = no. of coils per wave.

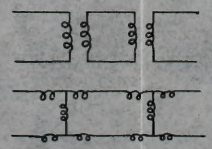
Loading Coils.

X





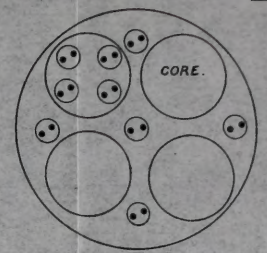
XI



Reed - Thompson cable.

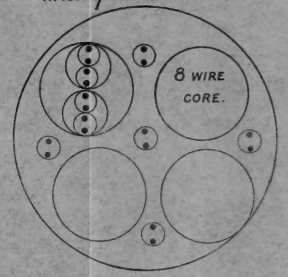
Quadruple Pair.

XII



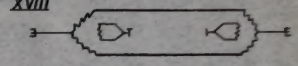
Multiple Twin.

XIII



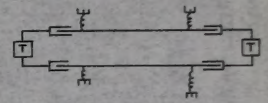
SIMPLEX.

XVIII

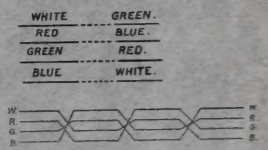


COMPOSITE.

XIX

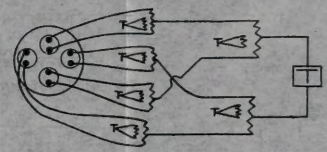


JOINTING.



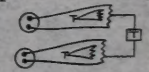
GHOST CIRCUITS (7 out of 8 wires).

XIV

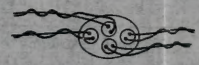


PHANTOM CIRCUIT.

XX

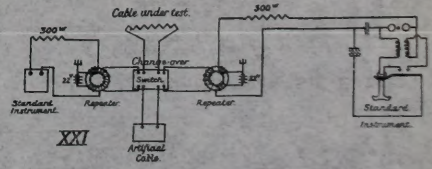


XV



BUNCHING.

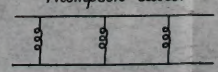
CIRCUIT FOR S.C.E. TEST



XXI

Thompson cable.

XVI



Artificial cable.

XVII